

## **Final Report**

### **Wavelet Compression of Satellite-Transmitted Digital Mammograms (sponsored by NASA-Lewis Research Center)**

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by

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## **Background**

Breast cancer is one of the major causes of cancer death in women in the United States. The most effective way to treat breast cancer is to detect it at an early stage by screening patients periodically. Conventional film-screening mammography uses X-ray films which are effective in detecting early abnormalities of the breast. Direct digital mammography has the potential to improve the image quality and to take advantages of convenient storage, efficient transmission, and powerful computer-aided diagnosis, etc. One effective alternative to direct digital imaging is secondary digitization of X-ray films. This technique may not provide as high an image quality as the direct digital approach, but definitely have other advantages inherent to digital images. One of them is the usage of satellite-transmission technique for transferring digital mammograms between a remote image-acquisition site and a central image-reading site. This technique can benefit a large population of women who reside in remote areas where major screening and diagnosing facilities are not available.

The NASA-Lewis Research Center (LeRC), in collaboration with the Cleveland Clinic Foundation (CCF), has begun a pilot study to investigate the application of the Advanced Communications Technology Satellite (ACTS) network to telemammography. The bandwidth of the T1 transmission is limited (1.544 Mbps) while the size of a mammographic image is huge. It takes a long time to transmit a single mammogram. For example, a mammogram of 4k by 4k pixels with 16 bits per pixel needs more than 4 minutes to transmit. Four images for a typical screening exam would take more than 16 minutes. This is too long a time period for a convenient screening. Consequently, compression is necessary for making satellite-transmission of mammographic images practically possible.

The Wavelet Research Group of the Department of Electrical Engineering at The Ohio State University (OSU) participated in the LeRC-CCF collaboration by providing advanced compression technology using wavelet transform. OSU developed a time-efficient software package with various wavelets to compress a series of mammographic images. This document reports the result of the compression activities.

## **Wavelet Transform**

Over the past decade, Discrete Cosine Transform (DCT) has been extensively used for the compression of still images. Based on DCT, JPEG ([1]) has been a widely accepted standard for image compression. Due to the use of block-based DCT in which the transform is performed on blocks of 8 by 8 pixels, JPEG tends to introduce annoying block artifacts at low bit rates which severely degrades the visual quality of the image. Wavelet transform is a new approach for image compression emerging in the past few years which has been proved superior to traditional DCT approaches. The wavelet transforms use two filter banks, low-pass (h) and high-pass (g), to localize the frequency distributions of an image globally. It out-performs the DCT transform because of the following advantages:

- Wavelet transform is applied to the entire image thus avoiding the block artifacts.

- Wavelet transform localizes signal characteristics in both time and frequency domains. Thus, more efficient exploration of spatial redundancies can be achieved.
- Wavelet transform supports continuous rate scalability. This allows the user to select a data rate according to the available bandwidth of the satellite communication link.

Figure 1 shows the block diagram of a typical wavelet transform ([2]).

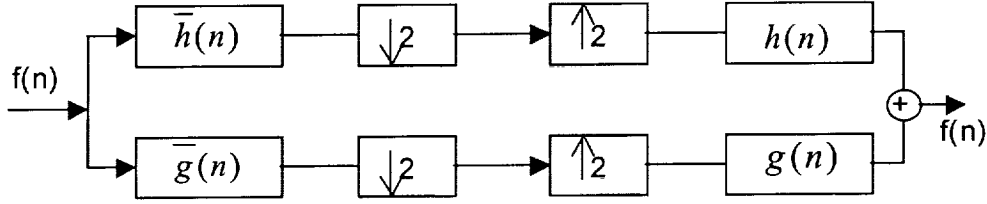


Figure 1 Wavelet analysis and synthesis of signal  $f(n)$  where  $\downarrow 2$  means down sampling and  $\uparrow 2$  means up-sampling.

One disadvantage associated with the conventional wavelet transform is the lengthy computation time. OSU developed a time-efficient software package which is based on a so-called packed-integer computation ([3]) which overcomes this disadvantage. The wavelets used in the computation are completely integer-based which is much faster than floating-point arithmetic.

### Activities

The Cleveland Clinic Foundation (CCF) provided OSU 50 digital mammograms. Each digital mammogram has a  $50 \mu m$  spatial resolution and 1.6 k by 4 k pixels with 16 bits per pixel. As a result, each image has 12.8 M bytes which will be too time-consuming to transmit by the T1 transmission line. These 50 mammograms represent different patient cases such as malignant microcalcification, benign microcalcification, malignant tumor, benign tumor, architectural distortion, and normal.

We used the SP and TS wavelets to perform the wavelet transform. Both TS and SP wavelets can be implemented using the integer computation ([4]). The low-pass and high-pass filters,  $h$  and  $g$ , of the TS transform can be expressed as

$$h = \left[ \frac{1}{2}, \frac{1}{2} \right] \quad (1)$$

and

$$g = \left[ -\frac{1}{8}, -\frac{1}{8}, 1, -1, \frac{1}{8}, \frac{1}{8} \right],$$

(2)

respectively. Those of the SP transform can be expressed as

$$h = [\frac{1}{2}, \frac{1}{2}] \quad (3)$$

and

$$g = [-\frac{1}{16}, -\frac{1}{16}, \frac{15}{32}, -\frac{17}{32}, \frac{7}{32}, -\frac{1}{32}]. \quad (4)$$

We first used the SP wavelets to compress the images using the compression ratios of 20:1, 60:1, 120:1, and 200:1, respectively. Then the TS wavelets were used to compress the images with compression ratios of 10:1, 20:1, and 60:1, respectively. Higher than 60:1 compression ratios such as 120:1 and 200:1 were dropped in the TS transform because they created too much distortion for reliable diagnosis in the SP transform. For each compression ratio, signal-to-noise ratio (SNR) was measured to compare the performance of the two wavelets. The compressed files were then used to reconstruct the mammograms which were reviewed by three radiologists at CCF for the preference study.

SNR is a numerical measure of the performance and is expressed as

$$SNR = 20 \log_{10} \frac{255}{RMSR} \quad (5)$$

where

$$RMSE = \sqrt{\sum_{i=1}^N \sum_{j=1}^M [f_{i,j} - f^*_{i,j}]^2} \quad (6)$$

where  $f_{i,j}$  represents the original direct digital mammogram and  $f^*_{i,j}$  represented the reconstructed images from the compressed files; N is the number of pixels in the x direction, and M in the y direction. A higher SNR represents a better quality of the reconstructed image.

In the preference study, three radiologists who specialize in mammography reviewed both compressed and uncompressed digital images. The 3 wavelet-compressed images (10:1, 20:1, and 60:1) were displayed simultaneously with the original mammograms. The readers ranked the images in order of preference where 1 is equal to the most desirable and

4 the least. A non-parametric rank-sum test was used to determine whether images compressed at different compression ratios differ significantly from the uncompressed original.

## **Results**

As just mentioned, OSU compressed the 50 mammograms with both SP and TS wavelets. The result of the SP transform is shown in Appendix A and the result of the TS transform is shown in Appendix B. From the result, one can see that the computation time for each compression is short (on average it is less than 3 seconds). If floating-point instead of integer arithmetic was used, the computation time would be 10 times longer. Secondly, one can see that the SNR ranges from 33 to 40 for compression ratios between 200:1 to 20:1. When SNR is about 40, the visual quality of the reconstructed image is very good and shows no significant difference from the original image. The difference between the TS and SP wavelets is not significant although the SP wavelets are slightly better in some cases. Additional 28 files were compressed using the TS transform and the 10:1, 20:1 and 60:1 compression ratios, respectively for CCF. All the compressed files were transferred to NASA-LeRC and CCF electronically for archive.

The SNR value is not always consistent with the perceive quality by human eyes. Therefore, it is important that the compressed mammograms be tested by the radiologists. This was conducted at CCF by three certified readers. The report of the study is attached as Appendix C.

The readers reviewed 68 cases with both calcifications and masses. The report indicated that for calcifications, the differences between the original and C10 (10:1 compression ratio) are not statistically significant. The difference between the original and C20 is statistically significant for reader 2 and marginally significantly for reader 1. The difference between the original and C60 is statistically significant for both readers.

For masses, the differences between the original and C10 (10:1 compression ratio) are statistically significant for reader 2. The difference between the original and C20 is statistically significant for both readers. The difference between the original and C60 is statistically significant for both readers.

Further details of the preference study can be found in Appendix C.

## **Conclusions**

From this initial study of wavelet transform for satellite-transmitted digital mammograms, we can draw a few conclusions:

- Wavelet transform is effective in compressing digital mammograms.
- Integer-based wavelets are computationally efficient and proved practical for compressing digital mammograms.

- Low compression ratio results in insignificant difference between the original and compressed images in the preference study. It appears that a lower than 10:1 compression ratio is necessary to eliminate the statistical significance by some of the readers.

We recommend to continuing the study by investigating more compression ratios until an optimal ratio is achieved. Another direction of future research is to use wavelet transform to enhance digital mammograms such that compressed images can reveal more diagnosis information even with a high compression ratio.

## References

1. G.K. Wallace, "The JPEG still picture compression standard," in *Communications of ACM*, Vol. 34, No. 4, pages 30-44, 1991.
2. C. Burrus, R. Gopinath, and H. Guo, Introduction to Wavelet Transforms, Prentice Hall, 1998.
3. C. Lin, B. Zhang, and Y.F. Zheng, "Packed integer wavelet transform constructed by lifting scheme," in *IEEE Transactions on Circuits and Systems for Video Technology*, Vol. 10, No. 8, December 2000, pp. 1,496-1,501.
4. H. Chao and P. Fisher, "An approach of fast integer reversible wavelet transform for image compression," Technical Report, Computer and Information Science Inc., Denton, Texas, 1996.

## **Appendix A Results of the SP Wavelet Transform of 50 Mammograms**



## Medical Image Compression Document

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**Software:** Medview—Medical Image Compression System.  
Copyright 1998-1999, OSU Wavelet Research Group.

**Images :** Mammography pictures from Cleveland Clinic Foundation.  
50 .raw files 1600\*4000\*2=12800000 bytes (12.2MB) each. B&W

### General Settings of the Medview:

Transform Type: SP transform  
Encoder : Stack Run  
Quantizer : S-DZ(best quality)  
Multiresolution : 5

### Compression Requirement:

Compress each image with 4 different compression ratio of 20:1, 60:1, 120:1 and 200:1 and produce the Reconstruction file for each ratio.

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Record No.: 1

File name :DL5K-A002\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A002_20	20:1	20.19:1	50	39.14	3214	3996	
A002_60	60:1	59.85:1	106	35.45	2754	3415	
A002_120	120:1	121.21:1	163	33.93	2724	3305	
A002_200	200:1	201.97:1	215	33.05	2654	3415	

Record No.: 2

File name :DL5K-A003\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A003_20	20:1	20.68:1	47	40.13	3184	3695	
A003_60	60:1	61.90:1	100	36.58	2754	3835	
A003_120	120:1	121.53:1	153	35.09	2724	3255	
A003_200	200:1	200.00:1	203	34.23	2654	3275	

Record No.: 3

File name :DL5K-A005\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A005_20	20:1	19.93:1	51	38.48	3126	3745	
A005_60	60:1	60.54:1	103	2734	2734	3335	
A005_120	120:1	119.42:1	153	2684	2684	3465	
A005_200	200:1	198.80:1	203	2674	2674	3264	

Record No.: 4

File name :DL5K-A006\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A006_20	20:1	20.68:1	57	38.96	3095	3955	
A006_60	60:1	59.00:1	110	36.07	2754	3365	
A006_120	120:1	120.30:1	166	34.69	2684	3345	
A006_200	200:1	198.68:1	210	33.94	2704	3315	

Record No.: 5

File name :DL5K-A009\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A009_20	20:1	20.61:1	44	37.00	3105	3705	
A009_60	60:1	59.53:1	83	34.30	2734	3646	
A009_120	120:1	119.70:1	118	33.24	2724	3305	
A009_200	200:1	198.08:1	150	32.64	2644	3224	

Record No.: 6

File name :DL5K-A010\_lobl.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A010_20	20:1	21.51:1	47	40.25	3095	3685	
A010_60	60:1	59.30:1	97	36.79	2754	3625	
A010_120	120:1	119.01:1	149	35.19	2734	2744	
A010_200	200:1	200.59:1	195	34.28	2674	3274	

Record No.: 7

File name :DL5K-A013\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A013_20	20:1	19.96:1	50	37.49	3124	3845	
A013_60	60:1	60.88:1	99	34.34	2733	3505	
A013_120	120:1	119.38:1	141	33.13	2724	3365	
A013_200	200:1	199.87:1	185	32.40	2664	3215	

Record No.: 8

File name :DL5K-A014\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A014_20	20:1	20.07:1	44	36.31	3175	3815	
A014_60	60:1	61.71:1	88	33.23	2754	3465	
A014_120	120:1	121.89:1	125	32.10	2734	3394	
A014_200	200:1	195.25:1	161	31.48	2744	3265	

Record No.: 9

File name :DL5K-A019\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A019_20	20:1	20.17:1	55	39.17	3105	3955	
A019_60	60:1	61.99:1	115	35.72	2764	3395	
A019_120	120:1	119.10:1	171	34.37	2724	3485	
A019_200	200:1	202.44:1	226	33.49	2654	3375	

Record No.: 10

File name :DL5K-A020\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A020_20	20:1	20.00:1	51	39.22	3110	3815	
A020_60	60:1	59.97:1	105	35.91	2734	3555	
A020_120	120:1	121.43:1	156	34.50	2664	3385	
A020_200	200:1	200.73:1	205	33.37	2684	3295	

Record No.: 11

File name :DL5K-A021\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A021_20	20:1	20.63:1	70	37.11	3095	3705	
A021_60	60:1	60.55:1	137	34.22	2804	3455	
A021_120	120:1	121.86:1	199	32.95	2674	3235	
A021_200	200:1	199.90:1	260	0.14**	2714	3264	

Record No.: 12

File name :DL5K-A024\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A024_20	20:1	19.96:1	45	41.18	3125	3626	
A024_60	60:1	61.77:1	96	37.71	2784	3445	
A024_120	120:1	119.69:1	144	36.25	2724	3234	
A024_200	200:1	200.31:1	195	35.30	2644	3365	

Record No.: 13

File name :DL5K-A026\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A026_20	20:1	20.29:1	59	37.37	3134	3585	
A026_60	60:1	60.82:1	114	34.39	2754	3465	
A026_120	120:1	121.80:1	166	33.19	2654	3245	
A026_200	200:1	200.67:1	210	32.53	2684	3355	

Record No.: 14

File name :DL5K-A027\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A027_20	20:1	20.90:1	42	40.35	3114	3605	
A027_60	60:1	59.53:1	90	36.47	2744	3505	
A027_120	120:1	120.45:1	145	34.70	2674	3315	
A027_200	200:1	198.74:1	195	33.67	2644	3325	

Record No.: 15

File name :DL5K-A028\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A028_20	20:1	20.17:1	44	39.53	3145	3736	
A028_60	60:1	59.51:1	91	36.11	2784	3515	
A028_120	120:1	119.09:1	137	34.70	2664	3265	
A028_200	200:1	199.30:1	180	33.86	2704	3275	

Record No.: 16

File name :DL5K-A030\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A030_20	20:1	20.18:1	56	39.32	3124	3816	
A030_60	60:1	59.08:1	113	36.24	2744	3415	
A030_120	120:1	119.58:1	168	34.88	2674	3294	
A030_200	200:1	200.43:1	222	34.09	2704	3405	

Record No.: 17

File name :DL5K-A031\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A031_20	20:1	20.80:1	44	39.85	3126	3675	
A031_60	60:1	61.25:1	90	36.48	2724	3425	
A031_120	120:1	120.58:1	132	35.16	2734	3285	
A031_200	200:1	201.59:1	176	34.35	2653	3355	

Record No.: 18

File name :DL5K-A032\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A032_20	20:1	20.98:1	51	40.24	3104	3566	
A032_60	60:1	59.32:1	105	36.80	2744	3565	
A032_120	120:1	118.13:1	161	35.27	2694	3404	
A032_200	200:1	201.83:1	216	34.34	2694	3335	

Record No.: 19

File name :DL5K-A036\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A036_20	20:1	20.74:1	38	39.55	3115	3795	
A036_60	60:1	60.18:1	77	36.03	2774	3485	
A036_120	120:1	120.95:1	115	34.55	2685	3305	
A036_200	200:1	203.75:1	155	33.71	2694	3435	

Record No.: 20

File name :DL5K-A040\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A040_20	20:1	20.51:1	51	39.20	3245	3876	
A040_60	60:1	59.64:1	105	35.87	2744	3485	
A040_120	120:1	121.3:1	156	34.45	2674	3254	
A040_200	200:1	202.0:1	205	33.69	2704	3385	

Record No.: 21

File name :DL5K-A040\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A040r_20	20:1	21.46:1	44	40.06	3154	3585	
A040r_60	60:1	61.63:1	92	36.39	2784	3385	
A040r_120	120:1	118.9:1	139	34.98	2714	3265	
A040r_200	200:1	203.2:1	183	34.06	2704	3344	

Record No.: 22

File name :DL5K-A045\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A045_20	20:1	19.74:1	37	38.51	3114	3795	
A045_60	60:1	60.11:1	78	34.86	2744	3415	
A045_120	120:1	120.6:1	115	33.41	2674	3335	
A045_200	200:1	204.6:1	155	32.58	2643	3325	

Record No.: 23

File name :DL5K-A046\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A046_20	20:1	19.96:1	38	39.49	3194	3685	
A046_60	60:1	61.24:1	83	35.60	2714	3505	
A046_120	120:1	119.6:1	125	34.12	2664	3324	
A046_200	200:1	203.5:1	174	33.09	2634	3275	

Record No.: 24

File name :DL5K-A048\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A048_20	20:1	19.15:1	40	37.73	3194	3625	
A048_60	60:1	61.96:1	83	34.44	2784	3355	
A048_120	120:1	124.2:1	119	33.26	2724	3255	
A048_200	200:1	199.6:1	155	32.57	2704	3275	

Record No.: 25

File name :DL5K-A052\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A052_20	20:1	21.26:1	40	38.57	3115	3675	
A052_60	60:1	61.36:1	85	34.89	2774	3465	
A052_120	120:1	121.4:1	127	33.40	2684	3255	
A052_200	200:1	200.4:1	170	32.53	2673	3294	

Record No.: 26

File name :DL5K-A057\_robl.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A057_20	20:1	20.34:1	60	38.85	3114	3685	
A057_60	60:1	59.14:1	119	35.87	2734	3505	
A057_120	120:1	122.5:1	181	34.47	2664	3345	
A057_200	200:1	198.7:1	235	33.76	2644	3275	

Record No.: 27

File name :DL5K-A058\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A058l_20	20:1	19.39:1	47	38.11	3124	3725	
A058l_60	60:1	61.37:1	92	35.15	2734	3475	
A058l_120	120:1	121.5:1	133	34.04	2674	3275	
A058l_200	200:1	201.9:1	174	33.34	2664	3335	

Record No.: 28

File name :DL5K- A058\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A058_20	20:1	20.94:1	41	38.99	3124	3695	
A058_60	60:1	62.72:1	76	35.96	2744	3405	
A058_120	120:1	118.0:1	106	34.88	2744	3305	
A058_200	200:1	204.2:1	140	34.09	2704	3325	

Record No.: 29

File name :DL5K-A060\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
A060_20	20:1	19.73:1	50	37.87	3184	3856	
A060_60	60:1	59.16:1	99	34.81	2794	3475	
A060_120	120:1	121.2:1	146	33.53	2724	3305	
A060_200	200:1	199.7:1	192	32.82	2674	3275	

Record No.: 30

File name :DL5K-B003\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B003_20	20:1	19.99:1	55	39.01	3104	3695	
B003_60	60:1	59.50:1	106	36.08	2734	3375	
B003_120	120:1	121.0:1	155	34.88	2664	3265	
B003_200	200:1	202.2:1	200	34.19	2634	3375	

Record No.: 31

File name :DL5K-B006\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B006_20	20:1	19.01:1	55	36.43	3126	3715	
B006_60	60:1	60.70:1	110	33.54	2724	3515	
B006_120	120:1	120.5:1	155	32.46	2664	3264	
B006_200	200:1	200.3:1	195	31.86	2633	3335	

Record No.: 32

File name :DL5K-B010\_lobl.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B010_20	20:1	21.02:1	50	39.06	3135	3645	
B010_60	60:1	60.83:1	100	35.83	2764	3445	
B010_120	120:1	122.2:1	153	34.39	2704	3314	
B010_200	200:1	200.8:1	200	33.60	2694	3315	

Record No.: 33

File name :DL5K-B012\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B012_20	20:1	21.71:1	43	37.97	3084	3765	
B012_60	60:1	61.54:1	85	34.72	2784	3515	
B012_120	120:1	122.8:1	125	33.40	2824	3304	
B012_200	200:1	204.5:1	165	32.62	2714	3385	

Record No.: 34

File name :DL5K-B019\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B019_20	20:1	21.38:1	34	39.54	3094	3535	
B019_60	60:1	60.68:1	72	35.75	2724	3505	
B019_120	120:1	122.2:1	112	34.11	2674	3295	
B019_200	200:1	204.8:1	151	33.13	2654	3385	

Record No.: 35

File name :DL5K-B020\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B020_20	20:1	19.59:1	39	37.45	3164	3615	
B020_60	60:1	60.26:1	77	34.38	2744	3505	
B020_120	120:1	122.2:1	110	33.25	2684	3365	
B020_200	200:1	196.9:1	139	32.66	2644	3345	

Record No.: 36

File name :DL5K-B024\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B024_20	20:1	20.83:1	35	38.43	3115	3745	
B024_60	60:1	62.75:1	70	35.26	2734	3535	
B024_120	120:1	117.7:1	97	34.17	2704	3364	
B024_200	200:1	203.8:1	125	33.40	2664	3324	

Record No.: 37

File name :DL5K-B028\_lobl.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B028l_20	20:1	19.81:1	44	37.93	3114	3806	
B028l_60	60:1	60.64:1	87	34.78	2734	3475	
B028l_120	120:1	122.1:1	130	33.40	2664	3565	
B028l_200	200:1	196.7:1	168	32.71	2644	3294	

Record No.: 38

File name :DL5K-B028\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B028_20	20:1	21.29:1	44	37.83	3114	3615	
B028_60	60:1	60.71:1	87	34.63	2724	3425	
B028_120	120:1	123.3:1	129	33.30	2664	3334	
B028_200	200:1	201.3:1	165	32.59	2644	3325	

Record No.: 39

File name :DL5K-B029\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B029_20	20:1	21.07:1	40	39.55	3114	3896	
B029_60	60:1	60.89:1	85	35.92	2744	3585	
B029_120	120:1	118.3:1	129	34.45	2684	3555	
B029_200	200:1	201.9:1	175	33.45	2643	3605	

Record No.: 40

File name :DL5K-B030\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B030_20	20:1	19.97:1	47	38.36	3124	3876	
B030_60	60:1	60.88:1	95	35.07	2744	3756	
B030_120	120:1	122.38:1	140	33.73	2674	3465	
B030_200	200:1	196.11:1	187	32.95	2704	3535	

Record No.: 41

File name :DL5K-B032\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B032_20	20:1	20.16:1	55	38.63	3114	3836	
B032_60	60:1	59.38:1	110	35.57	2744	3676	
B032_120	120:1	121.67:1	165	34.22	2724	3565	
B032_200	200:1	205.04:1	215	33.47	2663	3365	

Record No.: 42

File name :DL5K-B039\_rmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B039_20	20:1	21.06:1	45	35.97	3125	3775	
B039_60	60:1	58.06:1	85	33.03	2794	3525	
B039_120	120:1	118.96:1	125	31.70	2734	3515	
B039_200	200:1	196.68:1	165	30.96	2714	3405	

Record No.: 43

File name :DL5K-B041\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time(ms)	Decompression time(ms)	Total time
B041_20	20:1	20.02:1	38	38.12	3095	3885	
B041_60	60:1	60.23:1	77	34.06	2764	3705	
B041_120	120:1	118.6:1	110	33.37	2654	3555	
B041_200	200:1	201.3:1	143	32.55	2684	3424	

Record No.: 44

File name :DL5K-B043\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B043_20	20:1	20.90:1	40	40.06	3114	3776	
B043_60	60:1	60.97:1	85	36.33	2734	3635	
B043_120	120:1	121.4:1	127	34.86	2684	3445	
B043_200	200:1	200.0:1	171	33.97	2624	3345	

Record No.: 45

File name :DL5K-B048\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B048r_20	20:1	19.99:1	44	38.77	3094	3805	
B048r_60	60:1	59.19:1	94	35.20	2724	3776	
B048r_120	120:1	120.8:1	145	33.66	2664	3515	
B048r_200	200:1	200.2:1	192	32.82	2634	3465	



Record No.: 46

File name :DL5K-B052\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time(ms)	Decompression time(ms)	Total time
B052_20	20:1	20.65:1	37	38.63	3134	3896	
B052_60	60:1	59.81:1	72	35.39	2754	6816	
B052_120	120:1	120.2:1	104	34.11	2684	3555	
B052_200	200:1	202.7:1	136	33.33	2654	3565	

Record No.: 47

File name :DL5K-B053\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B053_20	20:1	19.54:1	45	39.33	3114	4016	
B053_60	60:1	61.44:1	92	35.90	2704	3866	
B053_120	120:1	121.7:1	135	34.63	2644	3845	
B053_200	200:1	201.9:1	179	33.86	2634	3746	

Record No.: 48

File name :DL5K-B053\_rcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B053r_20	20:1	19.88:1	43	37.96	3114	3895	
B053r_60	60:1	59.19:1	84	34.77	2714	3706	
B053r_120	120:1	120.6:1	119	33.64	2664	3575	
B053r_200	200:1	200.4:1	155	32.96	2633	3555	

Record No.: 49

File name :DL5K-B054\_lcc.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
B054_20	20:1	20.23:1	44	36.95	3105	3995	
B054_60	60:1	58.89:1	86	34.11	2734	3946	
B054_120	120:1	120.7:1	122	32.93	2664	3545	
B054_200	200:1	198.0:1	155	32.33	2643	3556	

Record No.: 50

File name :DL5K-C010\_lmlo.crop.raw

Filename	Expected Ratio	Actual Ratio	Step Size	SNR	Compression time	Decompression time	Total time
C010_20	20:1	19.19:1	54	36.77	3115	4036	
C010_60	60:1	61.64:1	108	33.58	2724	3735	
C010_120	120:1	123.0:1	156	32.39	2714	3525	
C010_200	200:1	198.0:1	199	31.80	2654	3496	

\*: The compressed files are named *filename.wif* and the reconstructed files are named *filename.raw*  
compression time (ms)

Disk1: A002—A036

Disk2: A020—A024, A040—A058

Disk3: A060, B003—B040

Disk4: B041—C010

## **Appendix B Results of the TS Wavelet Transform of 50 Mammograms**

## Medical Image Compression Document

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**Software:** Medview—Medical Image Compression System., Revised version.  
OSU Wavelet Research Group.

**Images :** Mammography pictures from Cleveland Clinic Foundation.  
50 .raw files 1600\*4000\*2=12800000 bytes (12.2MB) each. B&W

### General Settings of the Medview:

Transform Type: TS transform  
Encoder : Stack Run  
Quantizer : S-DZ(best quality)  
Multiresolution : 3

### Compression Requirement:

Compress each image with 3 different compression ratio of 10:1, 20:1, and 60:1 for the purpose of comparison with the original approach.

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Record No.: 1

File name :DL5K-A002 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	64	38.14	3175	3244
60:1	117	32.87	3105	3815
10:1	30	42.53	3666	3755

Record No.: 2

File name :DL5K-A003 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	38.91	3184	3695
60:1	121	36.58	2754	3835
10:1	27	41.83	3095	3365

Record No.: 3

File name :DL5K-A005 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	65	37.04	3524	2733
60:1	107	33.52	3165	3105
10:1	32	42.45	3893	3244

Record No.: 4

File name :DL5K-A006 lmlo.crop.raw

Expected	Step Size	SNR	Compression	Decompression
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Ratio			time	time
20:1	72	37.82	3175	3685
60:1	125	34.93	2754	3625
10:1	37	41.72	3734	2744

Record No.: 5

File name :DL5K-A009 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	57	35.93	3375	3894
60:1	92	33.26	2833	3015
10:1	25	40.87	3813	3013

Record No.: 6

File name :DL5K-A010 lbl.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	62	39.02	3095	3685
60:1	106	34.97	2754	3625
10:1	28	42.88	2734	2744

Record No.: 7

File name :DL5K-A013 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	73	35.82	3124	3845
60:1	111	33.16	2733	3505
10:1	36	38.93	2724	3365

Record No.: 8

File name :DL5K-A014 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	75	35.03	3175	3815
60:1	101	32.50	2754	3465
10:1	29	38.35	2734	3394

Record No.: 9

File name :DL5K-A019 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	75	37.82	3105	3955
60:1	128	34.16	2764	3395
10:1	34	39.65	2724	3485

Record No.: 10

File name :DL5K-A020 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	67	37.52	3110	3815
60:1	118	34.21	2734	3555
10:1	30	40.01	2664	3385

Record No.: 11

File name :DL5K-A021 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	91	36.24	3095	3705
60:1	148	32.97	2804	3455
10:1	48	38.04	2674	3235

Record No.: 12

File name :DL5K-A024 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	60	39.82	3125	3626
60:1	105	36.03	2784	3445
10:1	26	41.67	2724	3234

Record No.: 13

File name :DL5K-A026 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	71	36.15	3134	3585
60:1	132	33.21	2754	3465
10:1	37	38.93	2654	3245

Record No.: 14

File name :DL5K-A027 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	39.57	3114	3605
60:1	109	35.32	2744	3505
10:1	27	41.46	2674	3315

Record No.: 15

File name :DL5K-A028 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	64	37.92	3145	3736
60:1	115	35.43	2784	3515
10:1	32	39.85	2664	3265

Record No.: 16

File name :DL5K-A030 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	75	37.67	3124	3816
60:1	128	33.84	2744	3415
10:1	38	39.25	2674	3294

Record No.: 17

File name :DL5K-A031 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	64	38.41	3126	3675
60:1	113	35.37	2724	3425
10:1	29	40.16	2734	3285

Record No.: 18

File name :DL5K-A032 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	69	39.15	3104	3566
60:1	120	35.30	2744	3565
10:1	35	41.52	2694	3404

Record No.: 19

File name :DL5K-A036 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	52	38.36	3115	3795
60:1	94	34.92	2774	3485
10:1	24	40.52	2685	3305

Record No.: 20

File name :DL5K-A040 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	68	37.86	3245	3876
60:1	117	34.21	2744	3485
10:1	37	42.04	2674	3254

Record No.: 21

File name :DL5K-A040 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	64	38.43	3154	3585
60:1	115	36.39	2784	3385
10:1	26	41.86	2714	3265

Record No.: 22

File name :DL5K-A045 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	55	37.42	3114	3795
60:1	93	33.92	2744	3415
10:1	23	39.85	2674	3335

Record No.: 23

File name :DL5K-A046 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	38.12	3194	3685
60:1	98	33.96	2714	3505
10:1	27	40.42	2664	3324

Record No.: 24

File name :DL5K-A048 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	65	36.52	3194	3625

60:1	101	32.93	2784	3355
10:1	35	38.87	2724	3255

Record No.: 25

File name :DL5K-A052 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	57	37.57	3295	3775
60:1	104	33.12	2705	3132
10:1	28	39.21	3105	3375

Record No.: 26

File name :DL5K-A057 robl.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	78	37.14	3114	3685
60:1	132	34.65	2734	3505
10:1	39	39.72	2664	3345

Record No.: 27

File name :DL5K-A058 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	63	36.94	3124	3725
60:1	117	33.73	2734	3475
10:1	32	39.06	2674	3275

Record No.: 28

File name :DL5K-A058 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	59	37.85	3124	3695
60:1	93	35.26	2744	3405
10:1	32	40.32	2744	3305

Record No.: 29

File name :DL5K-A060 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	68	36.32	3184	3856
60:1	111	33.27	2794	3475
10:1	35	39.41	2724	3305

Record No.: 30

File name :DL5K-B003 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	73	37.92	3104	3695
60:1	120	34.57	2734	3375
10:1	39	40.02	2664	3265

Record No.: 31

File name :DL5K-B006 lmlo.crop.raw

Expected	Step Size	SNR	Compression	Decompression
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Ratio			time	time
20:1	71	35.26	3126	3715
60:1	124	32.45	2724	3515
10:1	37	38.14	2664	3264

Record No.: 32

File name :DL5K-B010 lobl.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	71	37.75	3135	3645
60:1	123	34.59	2764	3445
10:1	40	39.86	2704	3314

Record No.: 33

File name :DL5K-B012 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	36.37	3084	3765
60:1	101	33.51	2784	3515
10:1	28	38.81	2824	3304

Record No.: 34

File name :DL5K-B019 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	57	38.17	3094	3535
60:1	90	34.35	2724	3505
10:1	29	40.14	2674	3295

Record No.: 35

File name :DL5K-B020 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	36.54	3164	3615
60:1	93	32.97	2744	3505
10:1	32	39.43	2684	3365

Record No.: 36

File name :DL5K-B024 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	50	37.03	3115	3745
60:1	87	34.35	2734	3535
10:1	26	39.74	2704	3364

Record No.: 37

File name :DL5K-B028 lobl.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	58	36.53	3114	3806
60:1	104	33.83	2734	3475
10:1	35	38.40	2664	3565

Record No.: 38



File name :DL5K-B028 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	62	36.49	3114	3615
60:1	105	33.16	2724	3425
10:1	35	38.58	2664	3334

Record No.: 39

File name :DL5K-B029 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	56	38.21	3114	3896
60:1	99	34.67	2744	3585
10:1	25	40.52	2684	3555

Record No.: 40

File name :DL5K-B030 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	64	37.49	3124	3876
60:1	114	33.92	2744	3756
10:1	35	40.87	2674	3465

Record No.: 41

File name :DL5K-B032 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	71	37.15	3114	3836
60:1	123	34.37	2744	3676
10:1	38	40.72	2724	3565

Record No.: 42

File name :DL5K-B039 rmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	61	34.45	3125	3775
60:1	98	31.72	2794	3525
10:1	32	37.94	2734	3515

Record No.: 43

File name :DL5K-B041 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time(ms)	Decompression time(ms)
20:1	52	37.03	3095	3885
60:1	94	32.95	2764	3705
10:1	26	39.56	2654	3555

Record No.: 44

File name :DL5K-B043 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	57	39.12	3114	3776
60:1	103	35.21	2734	3635
10:1	28	41.51	2684	3445

Record No.: 45

File name :DL5K-B048 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	63	37.16	3094	3805
60:1	116	33.92	2724	3776
10:1	34	39.25	2664	3515

Record No.: 46

File name : DL5K-B052 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time(ms)	Decompression time(ms)
20:1	57	37.17	3134	3896
60:1	91	34.29	2754	6816
10:1	30	40.61	2684	3555

Record No.: 47

File name :DL5K-B053 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	60	38.46	3114	4016
60:1	112	34.80	2704	3866
10:1	31	40.27	2644	3845

Record No.: 48

File name :DL5K-B053 rcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	56	36.57	3114	3895
60:1	97	33.62	2714	3706
10:1	29	38.97	2664	3575

Record No.: 49

File name :DL5K-B054 lcc.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	65	34.34	3105	3995
60:1	107	32.19	2734	3946
10:1	29	38.16	2664	3545

Record No.: 50

File name :DL5K-C010 lmlo.crop.raw

Expected Ratio	Step Size	SNR	Compression time	Decompression time
20:1	74	33.89	3115	4036
60:1	120	31.21	2724	3735
10:1	37	37.92	2714	3525

\*: The compressed files are named *filename.wif* and the reconstructed files are named *filename.raw*  
compression time (ms)

Disk1: A002—A036

Disk2: A020—A024, A040—A058

Disk3: A060, B003—B040  
Disk4: B041—C010'

## **Appendix C Results of the Preference Study by the Cleveland Clinic Foundation**

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TO: Kim Powell, PhD  
 FROM: Nancy Obuchowski, PhD  
 DATE: May 8, 2000  
 RE: Compression Study Analyses

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For this analysis, two readers had data on 68 patients and one reader had data just on the original 40 patients. Thus, in this memo I describe the results for just the two readers with new data.

## Statistical Methods

We used signed rank tests to compare the scores assigned to the original image to the scores assigned to C10, C20, and C60. A significance level of 0.05 was used for each comparison. A separate analysis was performed for each of the 2 readers.

## Results

Tables 1 and 2 summarize the average rank of each of the 4 compression images for calcifications and masses, respectively. In parentheses we indicate the number of cases in which each image was assigned the highest preference (i.e. a score of 1). Note that there are several cases in which a reader assigned a score of 1 to more than one image.

For calcifications, the original image had the lowest average overall ranking for benigns, followed by C10; for malignants, the overall mean rank was the same for the original and C10. C20, then C60 followed. C10 was preferred in 32% of readings, C20 in 25%, and C60 in 22%, compared to the original which was preferred in 47% of readings.

For masses (table 2), the original image had the lowest average rankings overall, followed by C10, followed by C20, followed by C60. C10 was preferred in 29% of readings, C20 in 15%, and C60 in 29%, compared to the original which was preferred in 57% of readings.

Table 1: Descriptive Results for Calcifications

	ORIG	C10	C20	C60
<u>Reader 1</u>				
Malign. (N=17)	2.1 (7/17)	2.1 (7)	2.2 (6)	2.6 (4)
Benign (N=17)	1.6 (11/17)	2.1 (7)	2.5 (6)	2.4 (5)
<u>Reader 2</u>				
Malign. (N=17)	2.3 (5)	2.3 (4)	2.5 (3)	2.9 (4)
Benign (N=17)	1.7 (9)	2.4 (4)	2.9 (2)	3.1 (2)
<u>All</u>				
Malign. (N=34)	2.2 (12/34)	2.2 (11)	2.4 (9)	2.8 (8)
Benign (N=34)	1.6 (20/34)	2.2 (11)	2.7 (8)	2.7 (7)

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Mean ranks and number of cases in which the image was assigned the highest preference (given in parentheses).

Table 2: Descriptive Results for Masses

	ORIG	C10	C20	C60
<u>Reader 1</u>				
Malign (N=17)	1.5 (12/17)	2.1 (5)	2.2 (5)	2.4 (9)
Benign (N=17)	1.6 (8/17)	1.9 (9)	2.5 (3)	2.6 (4)
<u>Reader 2</u>				
Malign (N=17)	1.6 (11)	2.6 (1)	2.8 (0)	2.8 (5)
Benign (N=17)	1.9 (8)	2.2 (5)	2.8 (2)	3.1 (2)
<u>All</u>				
Malign (N=34)	1.6 (23/34)	2.4 (6)	2.5 (5)	2.6 (14)
Benign (N=34)	1.8 (16/34)	2.1 (14)	2.6 (5)	2.9 (6)

Mean ranks and number of cases in which the image was assigned the highest preference (given in parentheses).

For calcifications, the differences between the original and C10 are not statistically significant (see Table 3). The difference between the original and C20 is statistically significant for reader 2 and marginally significant for reader 1. The difference between the original and C60 is statistically significant for both readers.

For masses, the differences between the original and C10 is statistically significant for reader 2 (see Table 4). The difference between the original and C20 is statistically significant for both readers. The difference between the original and C60 is statistically significant for both readers.

Combining the data from calcifications and masses (see Table 5), the difference between the original and C10 is statistically significant for reader 2 and marginally statistically significant for reader 1. The difference between the original and C20 is statistically significant for both readers. Similarly, the difference between the original and C60 is statistically significant for both readers.

Table 3: P-values for Calcifications

	Reader 1	Reader 2
ORIG v. C10	0.302	0.258
ORIG v. C20	0.091	0.014
ORIG v. C60	0.040	0.006

Table 4: P-values for Masses

	Reader 1	Reader 2
ORIG v. C10	0.136	0.010
ORIG v. C20	0.002	<0.001
ORIG v. C60	0.004	0.002

**Table 5: P-values for Calcifications and Masses Combined**

	Reader 1	Reader 2
ORIG v. C10	0.083	0.011
ORIG v. C20	0.001	<0.001
ORIG v. C60	0.001	<0.001

## Conclusions

The results indicate that we cannot confidently replace the original image with any of these compressed images.